Study of Protective Meander Line Turn with Broad-side Coupling

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***Abstract*—Protection of electronic equipment against ultrashort pulses by meander lines is considered. The results of cross-section parametric optimization and experimental investigations of a meander line turn with broad-side coupling are presented. As the result of the optimization, the set of parameters is obtained for the line per-unit-length modal delays difference maximization with the geometric mean of modes impedances of 50 Ohm. Based on the selected parameters the printed circuit board with meander delay line prototypes of different lengths is manufactured. Then the study of the prototypes in time and frequency domains was executed. The attenuation of the ultrashort pulse with the duration of 40 ps up to 4.2 times is experimentally obtained. It is revealed that the turn passband decreased from 715 to 365 MHz with the turn length increasing from 50 to 100 mm.**

***Keywords*—meander line; protection; broad-side coupling; optimization**

I. INTRODUCTION

In the last few decades, it is more urgent to protect electronic equipment (EE) against unwanted influences. It is related to the reduction of the devices operating voltages and with the increasing of the packaging density of its inside the equipment, which leads to increased susceptibility to the unwanted influences. In case, the EE protection against intentional electromagnetic interference (IEMI), which increasingly used for the terroristic purpose as discussed even in the open sources becomes especially important. The first discussion of this problem began from the plenary lecture at the AMEREM conference in 1996 [1]. Soon, the first monograph on this subject was published [2]. The number of IEMI cases is registered, for example, a group of Chechen fighters used an ultrashort pulses generator to block the radio communication of Russian troops; security system of one of the largest British banks was blackmailed [3]. Nowadays, the IEMI problem is considered as an evident threat for infrastructure objects of Russian Federation (RF) fuel-power complex. In case, the system of RF standards for protection against IEMI was developed (the main GOST R 56103-14).

Especial danger among the IEMI is constituted by ultrashort pulses. For protection against them, the electromagnetic shields, special filters, decoupling devices, noise limiters and dischargers are used. However, they have a number of disadvantages, the most significant of which is insufficient response speed, low power, and stray parameters. These deficiencies make it difficult to protect against high-power ultrashort pulses. Implementation of protection in a range of interference parameters requires the developing of complex multistage devices whereas simplicity and cheapness are often important in a practice.

In case, the new approach to the EE protection in meander lines [4–7], based on the ultrashort pulse amplitude minimization by means of its decomposition in meander lines into a sequence of pulses with lower (relative to the original) amplitude [8–10]. To decompose the ultrashort pulse into a sequence of pulses we should provide some conditions that related the line parameters with signal duration. Within the framework of the investigation in this direction the meander line structure based on asymmetric strip line in air filling is firstly considered, where by the simulation and optimization the possibility of ultrashort pulse decomposition into two main pulses with equal and by 1.5 times lower amplitude (relative to the original) is shown [8]. In the line with inhomogeneous dielectric filling (for example, a microstrip), in general, the propagation velocities of signal even and odd modes are different, which can at the expense of used for ultrashort pulse additional attenuation of 1.5 times by its decomposition into three main pulses [9]. For the proof the noted possibility of EE protection against ultrashort pulses also the full-scale experiment on the example of one turn of meander microstrip line was carried out, where the ultrashort pulse attenuation up to 6.5 times is shown [11].

The continuation of these studies may be the investigation of protection devices and the possibilities of its developing based on the other lines types with the other parameters (for example, the line with broad-side coupling or the line consisting of several turns). Such studies will allow expanding the knowledge about the possibility of new protection devices developing, about the limits of ultrashort pulses attenuation, and also about the influence of the protective devices on the useful signals. In addition, these studies will define the possible areas of the protection devices application. The meander line turn with broad-side coupling, which is quite simple for implementation on printed circuit board (PCB) is suitable for such studies.

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The aim of this paper is to execute the optimization and experimental investigations in the time and frequency domains for the protective meander line turn with broad-side coupling. It requires executing preliminary simulation and optimization of the cross section parameters of the turn; designing and manufacturing a PCB with the set of line prototypes; conducting the full-scale experiment in the time and frequency domains.

II. INITIAL DATA FOR SIMMULATION

Cross section and circuit diagram of a line turn with broad-side coupling are shown in Fig. 1. All conductors have the same width (*w*) and the same thickness (*t*) and the letters «G» and «A» are given to indicate grounded and active conductors (Fig. 1*a*). The line consists of two parallel conductors (excluding the grounded conductor) of the length *l* interconnected at one end. One of the conductors is connected to a pulse source, which is presented by the e.m.f. source *E* and the resistance *R*1 and another conductor are connected to a receiving unit, which is presented as resistance *R*2. For the line simulation and optimization, the TALGAT software is used [12].

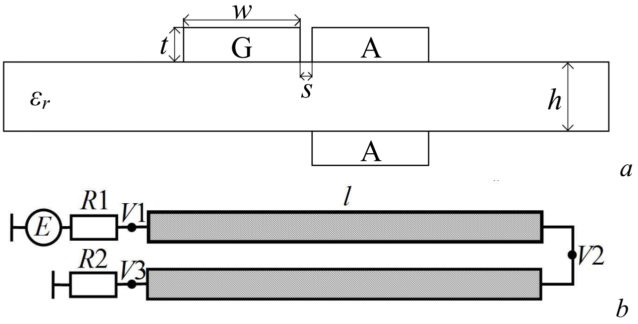


Fig. 1. Cross section (*a*) and circuit diagramm (*b*) of a meander line turn with broad-side coupling

Since the full-scale experiment will be carried out by means of an oscilloscope C9–11 (17.8 GHz bandwidth and 50 Ω internal impedance), the duration of a pulse provided by the generator is known (about 100 ps). For decomposition of the pulse with this duration twice the product of the *l* and the modulus of the per-unit-length mode delays differences should be bigger than 100 ps. To more clearly analyze the experimental results, it is desirable to minimize reflections in the measuring tract. This can be provided by equality of the geometric mean of the characteristic impedances of the line modes to the measuring tract impedance of 50 Ω.

The widely spreading material FR-4 is chosen as the substrate of PCB. In accordance to the datasheet of PCB manufacturer, the value of its dielectric permittivity at frequency 1 MHz ranges from 3.5 to 4.1. For simplicity, the average value of ε_r=3.8 is used in the simulation. Typical fixed cross section parameters, which changed discretely are the substrate thickness (*h* =500, 1000, 1500, 2000 µm) and conductor thickness (*t*=18, 35 мкм). Other parameters are variable: width of the signal conductor (*w*) and separation of signal and grounded conductors (*s*).

III. OPTIMIZATION RESULTS

First, we estimated the impact of the investigated line cross section parameters on the per-unit-length delays differences of the line modes ($\Delta\tau$) and on the geometric mean of its impedances (Z_C). It was found that the values of $\Delta\tau$ and Z_C for the different values of *t* are insignificantly differed (maximum deviation for $\Delta\tau$ equal to 2% and for Z_C – 1.3%), therefore the results are given only for *t*=18 µm. Dependencies of $\Delta\tau$ on *w* and *s* for different *h* are given in Fig. 2, 3, while the similar dependencies on Z_C are given in Fig. 4, 5. The value of *w* varied from 1 to 10 mm with step 1 mm (for *s*=0.2 и 1 mm), while of *s* – from 0.2 to 1 mm with step 0.1 mm (for *w*=1 и 10 mm).

The non-linear monotonically increasing dependence of $\Delta\tau$ on *w* is seen from Fig. 2. For *s*=0.2 mm and *h*=0.5 mm, $\Delta\tau$ has the largest values which are varying from 1.2 to 2.2 ns/m with increasing *w* from 1 to 10 mm. At *s*=1 mm we observe the similar dependencies behavior: values of $\Delta\tau$ move to higher values and vary from 1.6 to 2.6 ns/m with the increasing of *w* from 1 to 10 mm. With *h* increasing, the dependence of $\Delta\tau$ moves to lower values. The minimum value of $\Delta\tau$ correspond to *h*=2 mm and are equal to 0.56 and 1.59 n/m for *s*=0.2 and 1 mm respectively. Therefore, from the point of view of the maximizing of the ultrashort pulse duration, which can be completely decomposed in the line with fixed length *l*, it is preferable to chose a substrate material with *h*=0.5 mm with the largest value of *w*. From Fig. 3 we observe the similar behavior for dependencies of $\Delta\tau$ on *s*. But for *w*=1 mm, *h*=1.5 and 2 mm, $\Delta\tau$ changes slightly, and for *s*=0.2 и 0.3 mm the weakly expressed minimum is appeared and provide the minimal sensitivity of $\Delta\tau$ to the changes of *s*.

The nonlinear monotonically decreasing dependence of Z_C from *w* is seen in Fig. 4. With *h* increasing, the dependence of Z_C moves up. With the increasing of *w*, the value of Z_C decreases. The dependencies also show, that for all values of *h* the value of *w* for which Z_C=50 Ω exists. Thus, for *h*=0.5, 1, 1.5, 2 mm and *s*=0.2 mm the value of Z_C is 50 Ω for *w*=2.8, 4.7, 6 и 7.9 mm, while for *s*=1 mm – for *w*=4.6, 7, 9 and 10.5 mm respectively. Dependence of Z_C on *s* is monotonically increasing (Fig. 5). The lowest value of Z_C for *w*=1 mm corresponds to *s*=0.2 mm for *h*=0.5 mm and equals 79.96 Ω, while for *w*=10 mm it equals 25.26 Ω.

Based on the results of the computational experiment, the parametric optimization of a turn cross section was carried out. After the optimization, the parameters fulfilling the signal decomposition condition were obtained: *t*=18 µm, *s*=0.2 mm, *h*=1.5 mm, *w*=6 mm. For these parameters, the values of Z_C and $\Delta\tau$ are 50.36 Ω and 1.43 ns/m respectively. It follows from the last that decomposition of the pulse with the duration of 100 ps will be for *l*>35 mm.

I. FULL-SCALE EXPERIMENT RESULTS

Using the results of the preliminary simulation and optimization, a PCB with prototypes of meander line turns with *l*=50, 75, 100 mm has been manufactured, then the prototypes have been divided (Fig. 6).

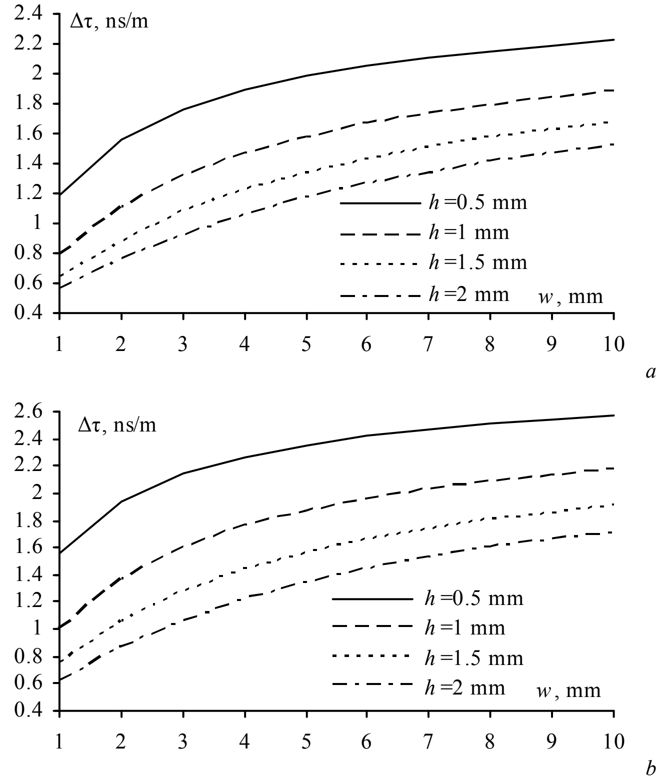


Fig. 2. Dependence of Δτ on *w* for different *h* with *s*=0.2 (*a*), 1 (*b*) mm

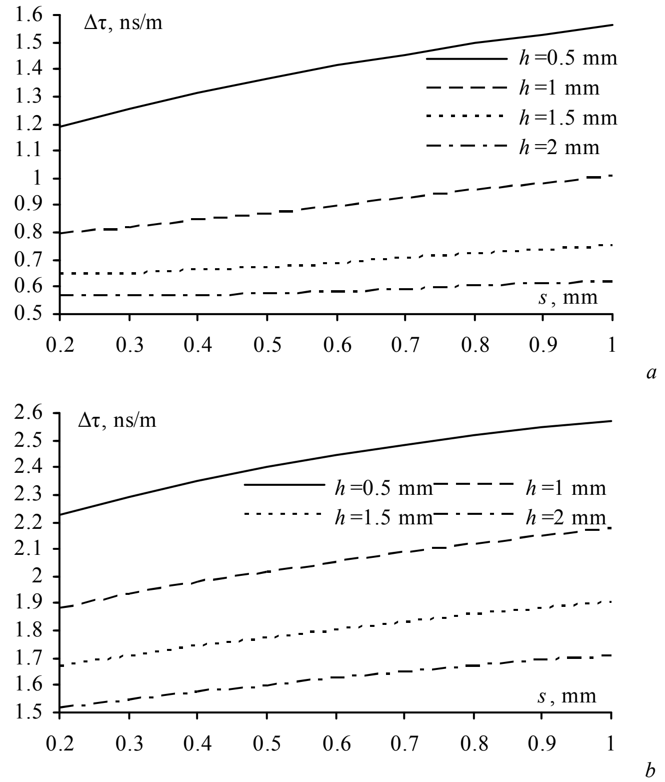


Fig. 3. Dependence of Δτ on *s* for different *h* with *w*=1 (*a*), 10 (*b*) mm

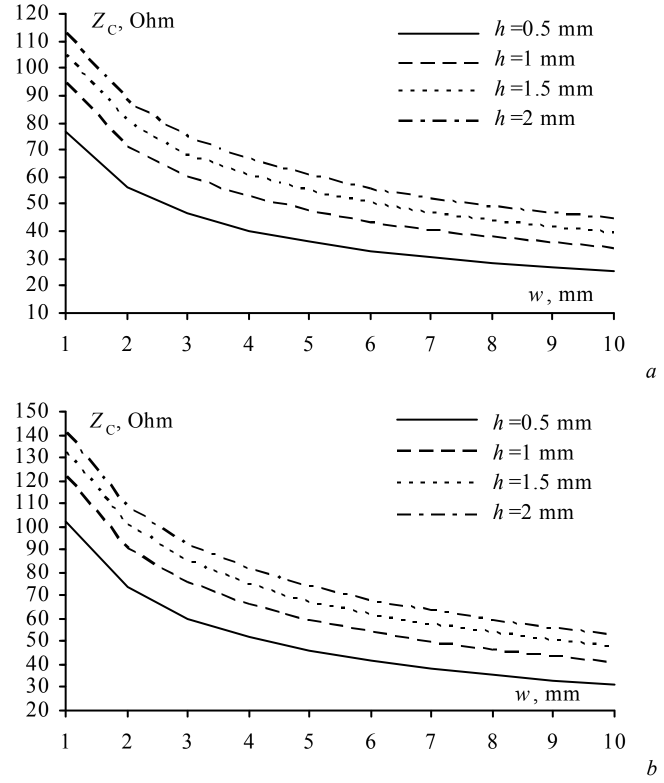


Fig. 4. Dependence of Z_c on *w* for different *h* with *s*=0.2 (*a*), 1 (*b*) mm

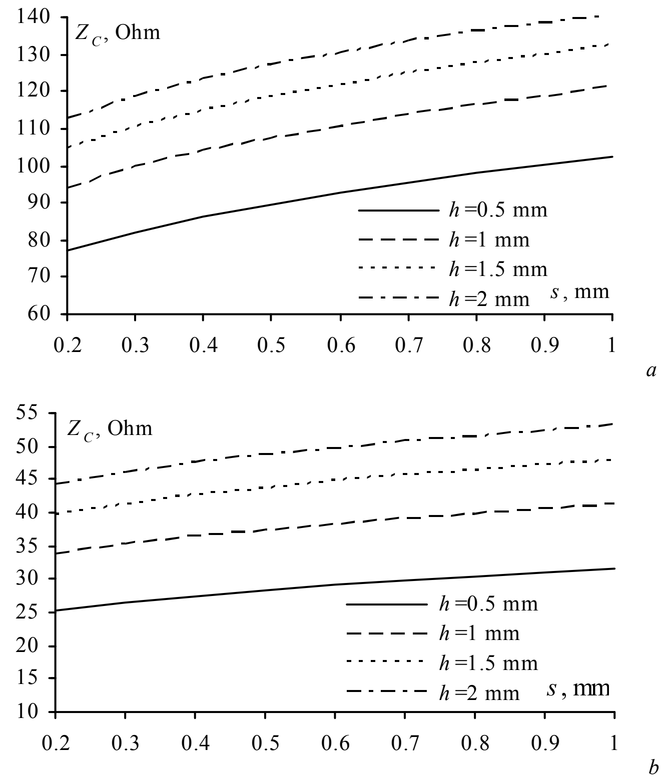


Fig. 5. Dependence of Z_C on *s* for different *h* with *w*=1 (*a*), 10 (*b*) mm

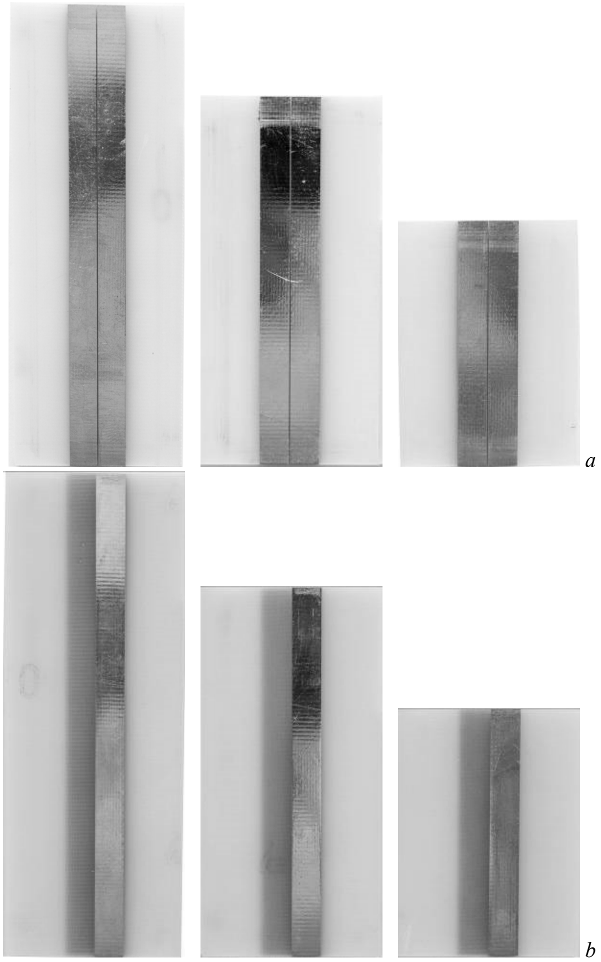


Fig. 6. Manufactured prototypes: top (*a*) and bottom (*b*) viewes

A. Time domain

During the time domain analysis, a signal from the output of the generator was supplied to the input of the combined oscilloscope C9-11 with the following parameters: amplitude 0.648 V, duration at half of the maximum level $t_{0,5}$=40 ps. Fig. 7 shows an oscilloscope record of a signal at the output of the generator.

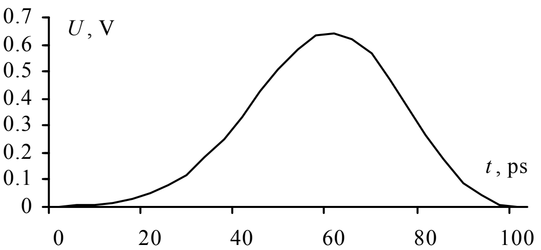


Fig. 7. Oscilloscope record of an exciting pulse at the 50 Ω load

The meander line turn prototypes were successively inserted between the output of the generator and the input of the oscilloscope C9-11 to record the waveforms using SMA connectors. Fig. 8 shows the digitized oscilloscope records of the signal at the output of each model.

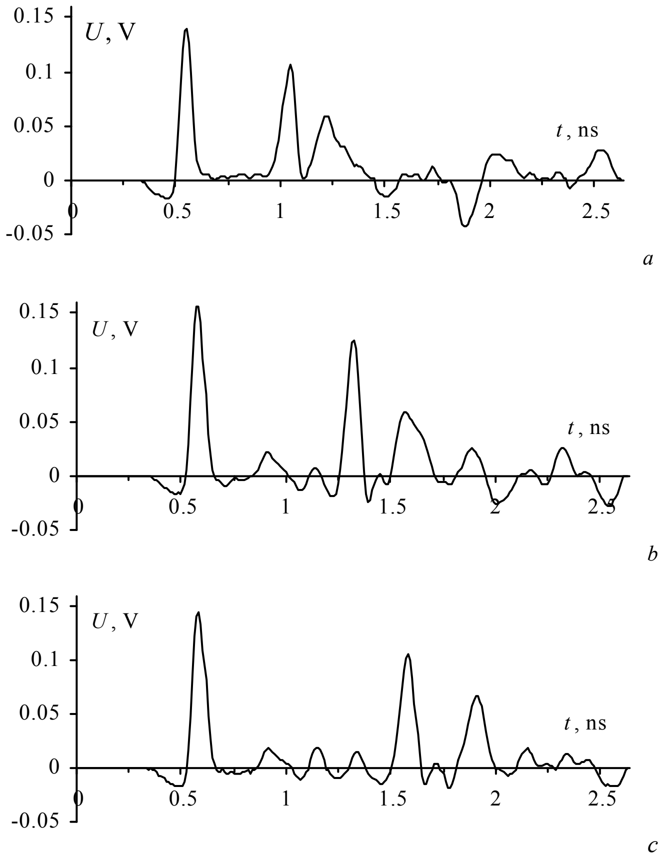


Fig. 8. Oscilloscope records of the signal at the output of prototypes for *l*= 50 (*a*), 75 (*b*) and 100 (*c*) mm

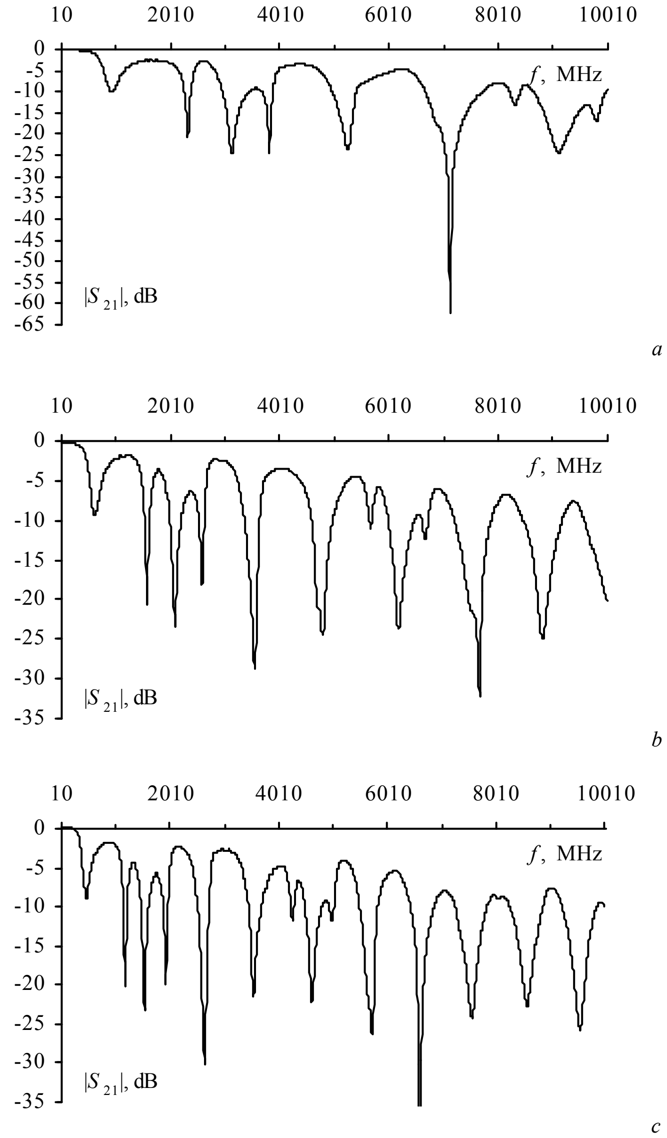
Oscilloscope records from Fig. 8 show that the signal comes to the end with the delay of 340 ps, which is according to the additional transition devices and SMA connectors necessary for its connection to the measuring tract. It is seen that the oscilloscope records have pulses with the low amplitude. They are caused by reflections from discontinuities of the measuring tract and from the connectors. The output signal, as in any coupled transmission line, is determined by superposition of the modes of the line. The signal in considered line is presented by the sequence of three main pulses (of the largest amplitude). In the simple explanation, the first pulse can be considered as a near-end crosstalk and the second and third are modes of the exciting pulse. It is also seen that with the line length increasing the second and third pulses arrival time is increased. The maximum signal level at the output of the prototypes is 24% of the signal level at the line input. However, it can be seen that it is determined by the first pulse level, so we have remained a small reserve of its reduction by some decoupling of conductors.

B. Frequemncy domain

For each prototype, the frequency dependence of the transmission coefficient magnitude $|S_{21}|$ using scalar network analyzer R2M40 was measured in the frequency range from 10 MHz to 10 GHz. The obtained dependencies of $|S_{21}|$ are shown in Fig. 9. The passbands for each of the turns at level –3 dB are summarized in Table I.

TABLE I. MEASURED PASSBAND OF PROTOTYPES

***l*, mm**	50	75	100
***f*, MHz**	715	475	365



a

b

c

Fig. 9. Measured frequency dependences of $|S_{21}|$ for prototypes with *l*= 50 (*a*), 75 (*b*) и 100 (*c*) mm

From the obtained results we can see multiresonant nature of the dependencies. The minimum value of $|S_{21}|$ is –62.2 dB at the frequency of 6.6 GHz for the turn with *l*=50 mm. Also from the obtained results, we can see, that the passbands of the turns at level –3 dB are different. The passband decreases by two times with the increasing the line length in by times. Thus, each of the prototypes will provide the propagation without distortions for the useful signals with the different highest frequencies.

II. CONCLUSIONS

The paper presents the cross-section parametric optimization and experimental investigation in time and frequency domains for protective meander line turn with broad-side coupling. As the result of the optimization, the set of parameters of the meander line turn is obtained for the line per-unit-length modal delays difference maximization for the pulse duration of 100 ps with the geometric mean of modes impedances of 50 Ohm to match the line with the tract. It is noteworthy that with this set of cross-section parameters values of the investigated line which are physically realizable by the typical PCB technology the values of Z_C can be achieved not only of 50 Ω (microwave tract) but also 75 Ω (television tract), 100 Ω (Ethernet) and etc. (Fig. 4, 5), which shows the possibility wide using of the paper results. The important possibility of the getting the also high Δτ values up to 2.6 ns/m (Fig. 2) using the cheap and widely used fiberglass is shown.

Based on the selected optimal parameters the PCB with meander delay line prototypes of different lengths is manufactured and the experimental investigations are carried out. In time domain the attenuation of the ultrashort pulse at the end of the meander line turn is demonstrated. It is noted that in the considered line the signal is presented as a sequence of three main pulses (with the largest amplitude). In the simple explanation, the first pulse can be considered as a near-end crosstalk and the second and third are modes of the exciting pulse. The maximum signal level at the output of the prototypes comprising 24% of the level of the signal with the duration of 40 ps at the line input is obtained. However, this level is determined by the first pulse level, so we have remained a small reserve of its reduction by some turn decoupling. In the frequency domain, the multiresonant nature of the protective turn transmission coefficient magnitude is demonstrated. It was determined that the passband of each turns at level –3 dB is different and has the inverse relation to the turn length. The frequency domain results together with the results in time domain make it possible to confirm that the meander line turn with broad-side coupling provides the EE protection against ultrashort pulses by means of its decomposition into sequence of pulses with the lower amplitudes and provides the useful signal propagations without essential distortions.

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